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When will the Antarctic ozone hole recover?

Paul A. Newman,[1] Eric R. Nash,[2] S. Randolph Kawa,[1] Stephen A. Montzka,[3] and Sue M. Schauffler[4]

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[1] The Antarctic ozone hole demonstrates large-scale, man-made affects on our atmosphere. Surface observations now show that human produced ozone-depleting substances (ODSs) are declining. The ozone hole should soon start to diminish because of this decline. We demonstrate a parametric model of ozone hole area that is based upon a new algorithm for estimating chlorine and bromine levels over Antarctica and late spring Antarctic stratospheric temperatures. This model explains 95% of the ozone hole area's variance. We then use future ODS levels to predict ozone hole recovery. Full recovery to 1980 levels will occur around 2068 and the area will very slowly decline between 2001 and 2017. Detection of a statistically significant decrease of area will not occur until about 2024. We further show that nominal Antarctic stratospheric greenhouse gas forced temperature change should have a small impact on the ozone hole. **Citation:** Newman, P. A., E. R. Nash, S. R. Kawa, S. A. Montzka, and S. M. Schauffler (2006), When will the Antarctic ozone hole recover?, *Geophys. Res. Lett.*, *33*, L12814, doi:10.1029/2005GL025232.

1. Introduction

[2] As ozone-depleting substances (ODSs) decline, full ozone hole recovery over Antarctica is expected about 2050 [*Hofmann et al.*, 1997; *World Meteorological Organization* (*WMO*), 2003]. *Hofmann et al.* [1997] fit ozone with ODS amounts over 12–20 km to estimate the recovery date. *WMO* [2003] estimated recovery based upon an ensemble of three-dimensional (3-D) models. Ozone recovery is expected in three phases: 1) a cessation of ozone decline, 2) a turnaround where ozone begins to increase, and 3) full recovery to 1980 levels. We define, for the ozone hole, phase 1 as a cessation of the growth of the ozone hole area, phase 2 as the year of peak area, and phase 3 as the date when the ozone hole has zero area.

[3] Recent analyses have shown that the ozone hole has entered this first phase of recovery because it is no longer growing [*Newman et al.*, 2004; *Huck et al.*, 2005; *Yang et al.*, 2005]. These analyses are based upon empirical fits of ozone hole diagnostics to effective equivalent stratospheric chlorine (EESC) and stratospheric temperatures. EESC is a convenient measure of ozone depleting stratospheric chlorine (Cl) and bromine (Br) levels that is estimated from ground-based measurements of halocarbons with assumptions about transit times into the stratosphere and rates at which halocarbons become destroyed in the stratosphere [*Prather and Watson*, 1990; *Daniel et al.*, 1995; *Montzka et al.*, 1999; *World Meteorological Organization* (*WMO*), 1999].

[4] This paper describes an estimate of the ozone hole's future based upon a parametric fit of the ozone hole's area to Cl and Br abundances and stratospheric temperature during the past 25 years.

2. Ozone Hole Area

[5] The ozone hole over Antarctica expanded rapidly in the 1980s, but that expansion slowed in the early 1990s, and appears to have stopped in the last few years. Figure 1 shows Total Ozone Mapping Spectrometer (TOMS) observed average ozone hole area (gray line). The area is determined from version 8 TOMS data for 21–30 September 1979–2004 (TOMS was not operational in 1995) and Ozone Monitoring Instrument data in 2005. The area is contained by the 220-DU contour in the Antarctic region. Values below this represent anthropogenic ozone losses over Antarctica [*Newman et al.*, 2004]. The ozone hole peak occurs during 21–30 September, prior to the late spring breakup when Antarctica is fully illuminated. Large area variations result from variations of stratospheric dynamics.

[6] While vortex collar ozone losses are driven primarily by the abundance of reactive Cl and Br species derived from ODSs [*Anderson et al.*, 1991], the temperature of the polar vortex collar region has a secondary impact on ozone-hole area [*Newman et al.*, 2004]. While Antarctic meteorological analyses are observationally derived, multidecadal observations of ODSs, and inorganic Cl and Br levels over Antarctica are unavailable. Therefore, it is necessary to estimate Cl and Br inside the stratospheric polar vortex from trace-gas measurements at Earth's surface and consideration of atmospheric mixing. *Newman et al.* [2004] fit ozone-hole area using polar vortex collar temperature and an estimate of EESC with a 6-year lag to account for the delay of ODSs and their products to arrive over Antarctica. They showed that the ozone hole is decreasing quite slowly because of the slow decrease of ODSs.

3. Estimates of Inorganic Chlorine and Bromine Abundances in the Stratosphere

[7] The gases that cause ozone loss (e.g., chlorofluorocarbons or CFCs and other gases) are released at Earth's surface, and are then carried from the troposphere into the stratosphere in the tropics. The Brewer-Dobson circulation transports these chemicals upward through the stratosphere and mesosphere in the tropics and subtropics and then

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]Science Systems and Applications, Inc., Lanham, Maryland, USA.
[3]NOAA Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado, USA.
[4]National Center for Atmospheric Research, Boulder, Colorado, USA.

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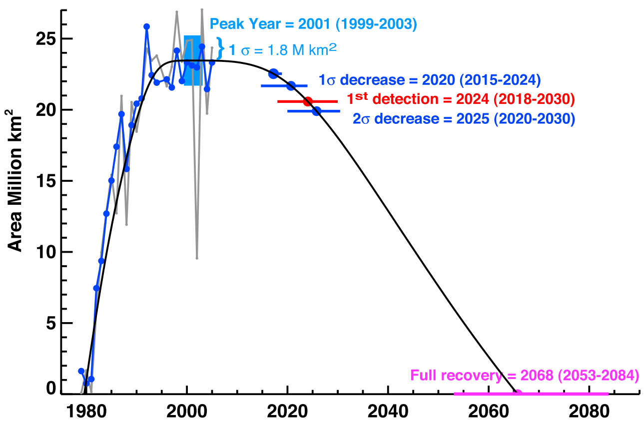

Figure 1. Ozone hole area averaged for 21–30 September daily values (gray line), along with temperature-corrected values (blue line). The area is fit to EEASC for 1979–2005, extrapolated using *WMO* [2003] scenario Ab (black line). The horizontal bars show uncertainties in date estimates. The vertical cyan bar represents a 1σ standard deviation.

downward over the poles. Air that is carried high in the stratosphere (>40 km) has a 5- to 6-year transit time from the tropical tropopause to a point inside the polar vortex in the Austral spring [*Waugh and Hall*, 2002]. Over such a 5-year period, 95% of $CFCl_3$ (CFC-11) is photolyzed from its organic form [*Schauffler et al.*, 2003]. This inorganic chlorine is transported downward from the upper stratosphere and mesosphere into the Antarctic polar vortex near 20 km during the Southern Hemisphere winter. Br has a similar pathway, but virtually 100% of the brominated compounds are converted to inorganic forms.

[8] ODSs are not regularly measured in the Antarctic stratosphere, requiring us to estimate their abundances and changes over time. Stratospheric ozone assessments [e.g., *WMO*, 2003] have estimated midlatitude stratospheric halogen levels using EESC from ground-based measurements of halocarbons [*Prather and Watson*, 1990; *Daniel et al.*, 1995; *Montzka et al.*, 1999; *WMO*, 1999]. See *WMO* [2003] for EESC calculation details.

[9] Standard EESC estimates [e.g., *WMO*, 2003] have three limitations when applied to the Antarctic stratosphere. First, EESC is estimated with a time lag of 3 years, a reasonable midlatitude time lag at 20 km, but inappropriate for the Antarctic lower stratosphere. Second, EESC is not estimated using a spectrum of air ages. Third, halogen release rates depend upon the time an air parcel spends in the stratosphere. For example, while about 47% of CFC-11 has decomposed after 3 years in the stratosphere, the fraction is closer to 100% after 6 years. Hence, age-of-air is crucial for correct estimates of total inorganic chlorine (Cl_y) and bromine (Br_y) in the Antarctic stratosphere (as well as other parts of the stratosphere). Standard EESC is inappropriate for application to the Antarctic stratosphere. The EESC used in *Newman et al.* [2004] had a 6-year time lag, but used midlatitude fractional release rates that were not appropriate for the Antarctic stratosphere.

[10] We have reformulated the EESC to more appropriately estimate Antarctic Cl_y and Br_y levels. This reformulation uses an appropriate age spectrum for air transported over Antarctica, and ODS fractional release rates that are dependent on the mean age-of-air (Γ). We summarize the calculation of equivalent effective Antarctic stratospheric chlorine (EEASC) below. Text S1 in the auxiliary material contains a detailed discussion of this new algorithm for estimating EESC in various regions of the stratosphere.[1]

[11] The degraded products or released fractions of ODSs have been calculated from aircraft observations [*Schauffler et al.*, 1999, 2003]. We first use the time series of surface observations from *Prinn et al.* [2000] to calculate the levels of total Cl and Br over Antarctica convolved with our age-of-air spectrum. Following *Schauffler et al.* [1999, 2003], we calculate fractional release rates for all species. This technique provides ODS fractional release for Γ up to about 6 years. Thus, given Γ, we can estimate Cl_y and Br_y anywhere in the stratosphere from the ground observations.

[12] Age-of-air over Antarctica has been estimated from both models and limited observations. *Waugh and Hall* [2002] estimated $\Gamma \approx 6$ y to explain globally-averaged HALOE HCl observations at 55 km. Since air is advected downward from the upper stratosphere into the core of the vortex over the course of the Antarctic winter, we estimate $\Gamma \approx 5$–6 y inside the lower stratospheric polar vortex. *Andrews et al.* [2001] have calculated $\Gamma \approx 5$ y in the Antarctic vortex in the Austral spring using aircraft observations of CO_2 at the edge of the Antarctic polar vortex. A $\Gamma \approx 5$ y in the Arctic lower stratosphere is a lower bound on the Antarctic value because of the more dynamically mixed nature of the Arctic [*Waugh and Hall*, 2002]. To generate our estimate of EEASC we use $\Gamma = 5.5$ y, an age spectrum width (Δ) of 2.75 y [see *Waugh and Hall*, 2002], and a bromine scaling factor (α) of 50 [*Chipperfield and Pyle*, 1998].

4. Parametric Model of the Ozone Hole

[13] Following *Newman et al.* [2004], the Antarctic ozone long-term trend is well explained by ODS trends. Year-to-year variability can be mainly explained by temperature variability of the collar. We use our new estimate of EEASC and temperature to regress against the observed area of the ozone hole (grey line in Figure 1). Temperatures are from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data. Temperatures are averaged over 60°–75°S for 11–30 September at 50 hPa (approximately 20 km in altitude). The EEASC and temperature are regressed as quadratic functions against ozone hole area: $A_i = aE_i + bE_i^2 + cT_i + dT_i^2 + \varepsilon_i$, where i represents the year, E is EEASC, T is temperature, and ε is the residual error. If we constrain the maximum area to occur when EEASC is a maximum then $b = -a/(2E_{\max})$, where $E_{\max}$ is the maximum value of EEASC.

[14] The regression of these two variables explains 95.6% of the ozone hole area variance (correlation of 0.978). The residual standard deviation (σ) is estimated as 1.8 million km^2 from the ε_i (indicated by the cyan bar in Figure 1). The blue points in Figure 1 show the area with the temperature

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005gl025232.

terms removed ($A_i - cT_i - dT_i^2$) and the black line shows the area fit to just the EEASC ($A_i = aE_i + bE_i^2$).

[15] Figure 1 shows that the ozone hole reached a peak value in the early 1990s, but has varied considerably over the last decade. Peak EEASC occurred in 2001 for Γ = 5.5 y. Because of the peak in EEASC, the "fit" area also peaks in 2001. The rapid late 1980s growth and the small increases of area in the mid 1990s occurred as EEASC steadily increased. This implies that the ozone losses in the vortex edge had saturated in the 1995–2005 period [*Newman et al.*, 2004].

[16] The residuals (ε_i, σ = 1.8 million km^2) have various sources. The large 1992 deviation resulted from stratospheric sulfate aerosol enhancements by Mt. Pinatubo [*Hofmann et al.*, 1997]. From our temperature regression, a deviation of 1 million km^2 is equivalent to a temperature uncertainty of about 1 K. Comparisons of monthly mean radiosondes and 100-hPa temperatures show good agreement to about 1 K with some pronounced biases in October and November [*Marshall*, 2002]. The gradient of ozone near the 220-DU level is approximately 0.121 million km^2 DU^{-1} [*Newman et al.*, 2004]. Hence, the 5-DU year-to-year uncertainty in the 220-DU value (R. McPeters, private communication, 2005) is equivalent to a 0.6 million km^2 year-to-year area error. The residual areas are probably a combination of: sulfate aerosol interannual variability, errors from both TOMS and the temperatures, and misestimates of the EEASC over Antarctica.

5. Parametric Model Estimates of Ozone Hole Recovery

[17] We use future ODS scenarios in our parametric model to predict future ozone hole behavior. The parametric model prediction (black line) is shown in Figure 1 using scenario Ab from *WMO* [2003] for Γ = 5.5 y and Δ = 2.75 y. The area remains large for at least the next decade and begins to decrease in about 2017. This plateau period of relatively unchanged area contrasts with the sharper peak of EESC that has been calculated from surface observations [*WMO*, 2003]. The plateau results from the insensitivity of ozone losses over Antarctica to current Cl and Br levels (i.e., loss saturation) plus the slow decline in ODS abundances. While the ozone hole turnaround occurred in approximately 2001 (based upon our EEASC), this slow decline will not be immediately detectable against the random ozone hole size variability of 1.8 million km^2.

[18] Full ozone hole recovery to a zero area is projected to occur in 2068, 18 years later than the current *WMO* [2003] recovery estimate based upon 3-D model estimates. From the peak value in 2001, there will be a very slow decline until 2017, and then the area will decrease by 1σ in 2020 and 2σ in 2025.

[19] The uncertainty in our area fits to the observations arises from uncertainties in Γ, Δ, and EEASC. The propagation of these uncertainties on our projections is calculated by performing Monte Carlo simulations of the EEASC and by using a bootstrap technique on the area estimate. A new area time series for 1979–2005 is simulated by adding the original area fit (black line in Figure 1) to a random sampling of the residual errors (deviations of the blue points from the black line). The EEASC time series is calculated with Gaussian distributions of Γ (σ = 0.5 y), Δ (σ = 0.5 y), and random variations (σ = 80 ppt) to the EEASC to account for transport variations. The 80 ppt is estimated from interannual variability in a chemical transport model [*Kawa et al.*, 2002], caused by interannual variability of vertical advection and mixing that affects Cl_y, Br_y, and Γ estimates. We then use 8500 area and EEASC simulations of the 1979–2005 period to recompute the regression of ozone area against EEASC.

[20] The 95% uncertainty in final recovery is from 2053–2084 (horizontal magenta bar in Figure 1), while the 95% uncertainty in a 1σ decrease of area is 2015–2024 (horizontal blue bar). The largest sensitivity in recovery results from the Γ estimate. Using Γ = 5 y (Δ = 2.5 y) results in a recovery date of 2058, while using Γ = 6 y (Δ = 3 y) gives a recovery date of 2074. Increasing α to 60 increases the recovery time by approximately 2 y.

[21] A statistically significant decline in Antarctic ozone hole area from the plateau period (the "first detection" year) will not be detectable until about 2024. We estimate this year by calculating the linear downward trend calculated for each year from 2003 and using our estimated σ = 1.8 million km^2 with a Student's *t*-distribution. Up to 2015 the trend is near zero and progressively becomes more negative each year beyond 2017 as the area decline accelerates. The 2024 "first detection" year occurs after the ozone hole has decreased in area by approximately 3–4 million km^2 (1–2σ) from the 23.7 million km^2 mean peak. In addition to this linear technique, we have used the CUSUM technique [*Yang et al.*, 2005] to estimate the first detection of turnaround date. In the CUSUM technique, we simulate the ozone hole from 2003–2040 using the black line in Figure 1 with resampled residual errors for each year from our residual deviations. We perform 10,000 simulations and calculate the CUSUM for each simulation. We find that 95% of the CUSUMs are negative after 2024, consistent with the first detection discussed above.

[22] Our full recovery times are later than *Hofmann et al.* [1997] and *WMO* [2003]. The EEASC used in their study was taken from ODS measurements from *World Meteorological Organization* (*WMO*) [1995], had a 3-year time lag with respect to the surface observations, no age spectrum, α = 40, and fractional release rates from *Daniel et al.* [1995]. They concluded that first signs of recovery would occur in the 2008–2010 period with a 2050 full recovery. In contrast, our results have a 5.5-year age spectrum, updated ODS levels from *WMO* [2003], α = 50, and updated fractional release rates. The main difference with the *Hofmann et al.* [1997] study is the longer age, with additional constraints supplied from the longer observational records. Chemistry-climate models (CCMs) predict a start to Antarctic recovery (first increase) in the range of 2001–2008 and full recovery "by about 2050," however, these predictions considerably underestimate the ozone hole area [*Austin et al.*, 2003]. A much later full recovery date can be derived if the area decrease or "trend" rate from the CCMs is used in combination with the higher TOMS observations of area.

[23] We have also estimated recovery from October monthly mean minimum and 65°–75°S zonal-mean ozone. We choose an initial point as the average of the 1979–1980 value, consistent with the ozone hole area estimate. From

the October minimum and the zonal mean we obtain a recovery date of 2063, reasonably consistent with the area recovery date of 2068. The first detection of recovery is estimated to be 2023 for the October minimum and 2025 for the zonal mean, again consistent with the area-based estimate of 2024.

6. Future Scenarios

[24] In the presence of elevated Cl and Br, the ozone hole area is strongly related to temperature. Climate assessment models estimate an Antarctic lower stratosphere cooling of approximately 0.25 K decade^{-1} [*Intergovernmental Panel on Climate Change*, 2001]. From our temperature regression coefficients, this cooling would increase the ozone hole area by approximately 0.2 million km^2 decade^{-1}. During the 2020–2030 period, these regression coefficients suggest that the area will be decreasing by 3–5 million km^2 decade^{-1}, so the climate change cooling will have small impact and will modestly delay the first detection of a diminishing ozone hole area by approximately one to two years. We estimate that the cooling will delay full recovery by approximately four years. This small delay is uncertain because of: 1) the uncertain magnitude of the cooling, 2) the impact of climate change on the stratospheric circulation and age-of-air, 3) the assumption that the influence of temperature on ozone loss rates in the past is representative of future loss rates, and 4) uncertain predictions of future stratospheric aerosols, water vapor and their influence on heterogeneous reaction rates.

[25] This parametric model can be used to test future scenarios of ozone hole recovery. As an example, we have modified methyl bromide (CH_3Br, a natural compound and also an agricultural fumigant) in *WMO* [2003] scenario Ab. Current levels of CH_3Br are specified in their scenario to maximize in 1999 at 9.5 ppt and fall to a fixed level of about 8.2 ppt by 2016 because of production phase out. CH_3Br has a short life-time of only 0.7 years. If we permanently fix CH_3Br at 9.5 ppt and adjust the EEASC into the future, we estimate ozone hole full recovery is delayed by 3.7 years. We have also tested the scenario for the new 2006 ozone assessment. The full recovery date increases slightly to 2070, and the date of first detection remains unchanged.

7. Conclusions

[26] We estimate Antarctic ozone hole recovery using the ozone hole's area as our prognostic variable. *Newman et al.* [2004] showed that: 1) the area was primarily controlled by Cl_y, Br_y, and temperature, 2) the area was no longer strongly increasing, 3) the ozone hole was decreasing at a very slow rate of approximately 1% per year based upon the slow decrease of Cl_y and Br_y estimates, and 4) the slow decrease would be masked by year-to-year variability. This work extends the ozone hole area estimates into the future using Cl_y and Br_y projected values to 2100.

[27] We calculate EEASC over Antarctica using a new algorithm that uses an age-of-air spectrum with a 5.5-year mean age that is consistent with ODS fractional release rates. The Cl_y estimate over Antarctica shows reasonable agreement with HALOE HCl observations (see Text S1). Because of the 5.5-year mean age used here, previous studies that used a 3-year shift of EESC [e.g., *WMO*, 2003] over Antarctica had EESC peaking in 1997, at least two to three years earlier than would be expected and with an inappropriately stronger decrease in EESC decrease during the 1998–2005 period.

[28] Based upon our new estimates of EEASC, we estimate that the Antarctic ozone hole will fully recover in about 2068, 18 years later than the latest *WMO* [2003] estimate. Using a conventional linear analysis, the turnaround of the ozone hole's area will not be statistically detectable until about 2024 (after removal of temperature effects). In contrast to the *Newman et al.* [2004] estimate of a 1% per year decrease of ozone hole area, we now estimate that the ozone hole is decreasing in area by less than 0.3% per year until about 2010 with recovery accelerating after this slow decrease period.

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S. R. Kawa and P. A. Newman, NASA Goddard Space Flight Center, Code 613.3, 8800 Greenbelt Road, Greenbelt, MD 20771, USA. (paul.a.newman@nasa.gov)

E. R. Nash, Science Systems and Applications, Inc., 10210 Greenbelt Road, Suite 600, Lanham, MD 20706, USA.

S. A. Montzka, NOAA Earth System Research Laboratory/Global Monitoring Division, 325 Broadway R/GMD1, Boulder, CO 80305-3328, USA.

S. M. Schauffler, National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, CO 80305, USA.